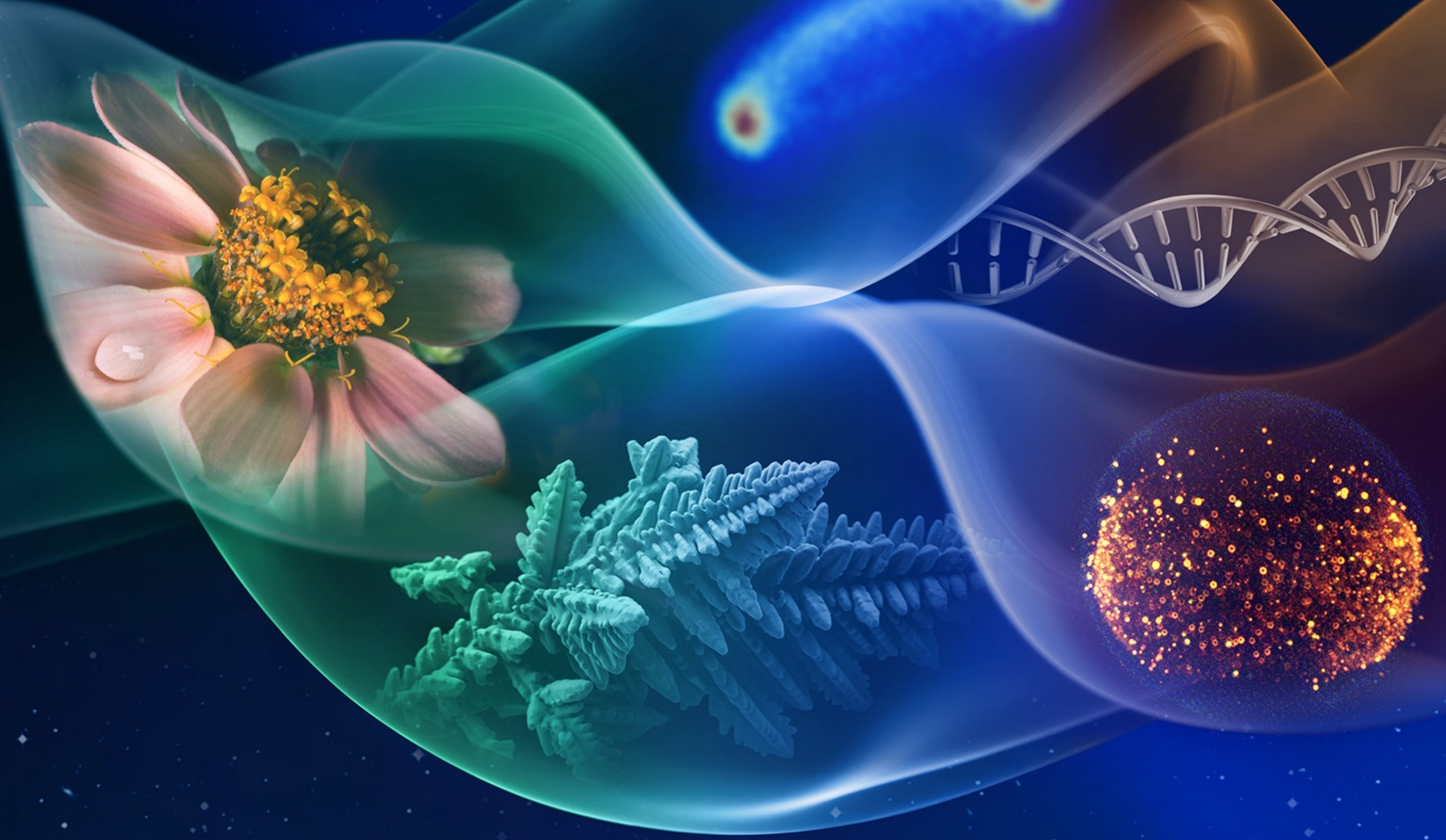
Perspectives of Soft Matter Research in Space



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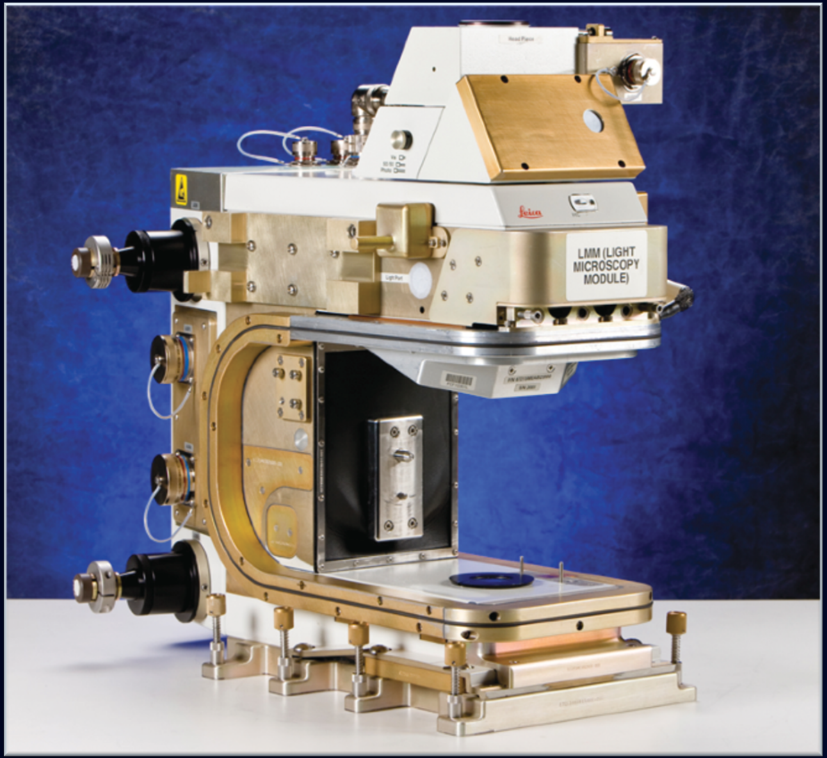
The ISS Workhorse for NASA's Colloids Research



Launched on Shuttle 17A – August 2009
Forty experiments over 11 years
Used by 8 countries and 24 universities
18,100 operational hours

- Modified commercial confocal microscope
  - Leica RXA microscope with high resolution camera
  - Developed by ZIN Technologies Incorporated and GRC
- On International Space Station (ISS)
  - In Fluids Integrated Rack (FIR)
- Samples loaded by crew
- Operated from GRC Telescience Center

Why Study Soft Matter (Colloids)?

- Emergent behavior
  - Cannot be predicted from nearest-neighbor interactions
  - Lacks general mathematical description
- Colloidal systems are a preferred model for complex systems
  - Large particle number
  - Well-characterized interactions
  - Good observation techniques (e.g., confocal microscopy)

Why Study Soft Matter in Space?

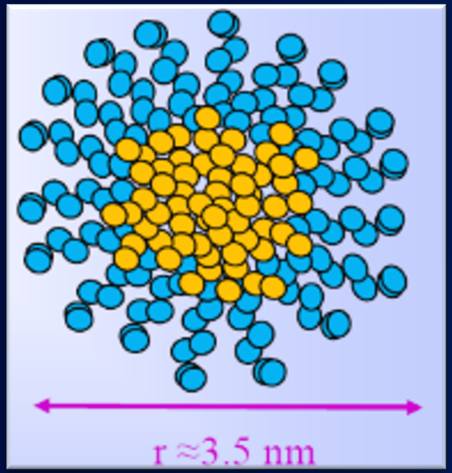
- Colloidal particles sediment in 1-*g*
  - Many terrestrial studies are limited to 2D systems
  - Density matching only possible for single particle types and narrow temperature range
- Microgravity reduces sedimentation (and buoyancy-driven convection)
  - Enabled study of 3D systems from hours to days in length

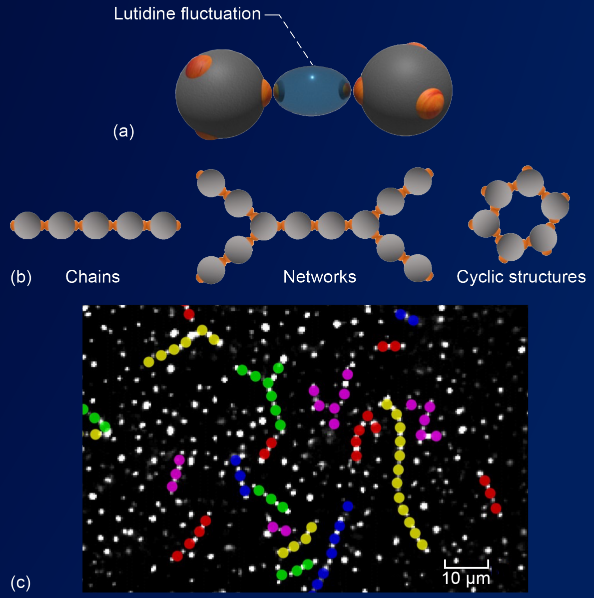
ACE–T Experiments

With 3D Confocal and Temperature Control 2016 to 2021

- ACE-T10-1 and -2
  - Crystal nucleation
  - Origin of aging in glasses and gels
  - Heterogeneous dynamics

- ACE-T2 Critical Casimir Forces
  - Micron-scale particles
  - Assembly of complex structures via tunable attractive interactions





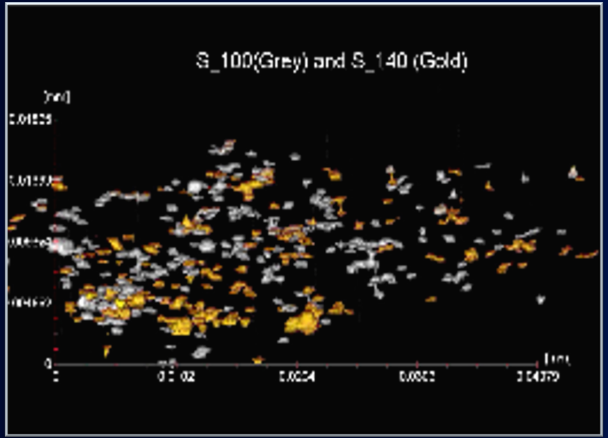
a. Colloids binding via their patches.
b. Possible structures of pure di-patch (left), mixtures of di- and four-patch (center) and four-patch particles (right).
c. LMM with superimposed colored dots illustrating the assembled particles clusters.

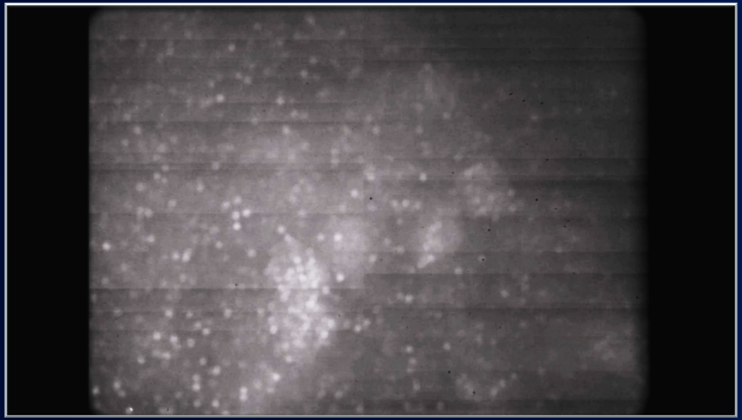
ACE–T Experiments

With 3D Confocal and Temperature Control 2016 to 2021

- ACE-T6 Colloidal Stabilizers
  - Fundamental interactions in gels and creams
  - Long term stability

- ACE-T7 Cubes
  - Design and creation of complex “self-assembled” 3D structures
  - Potential applications include advanced optical switches and high performance battery electrodes





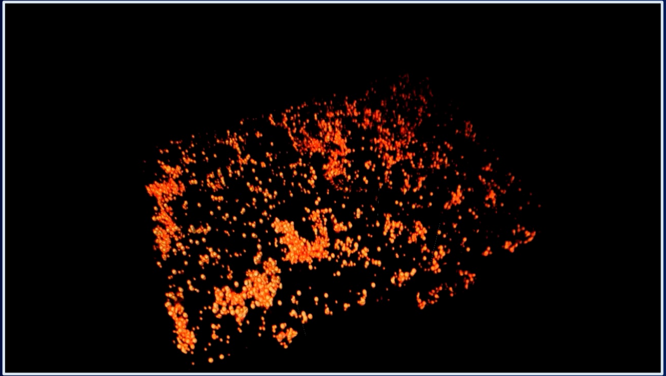
One ACE-T7 slice from a confocal stack that shows large 3D crystals forming – not seen on Earth. Data analysis underway.

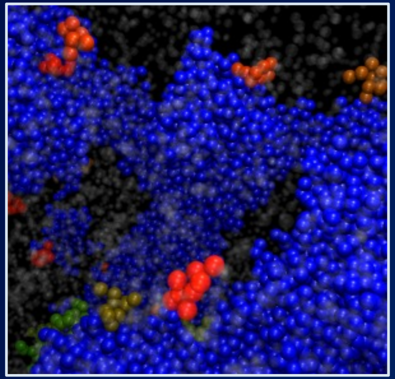
Advanced Colloids Experiment (ACE)

Enabling Soft-Matter Microgravity Research
Fundamental Science and Colloidal Engineering at the Particle Level

Advanced Colloids Experiment—Manual/Passive (ACE–M) 2013 to 2021

- ACE–M1 (Matthew Lynch, The Procter & Gamble Company)
  - Fundamental research on stability of systems
  - Applied to commercial product development
    - Patents: US 10,076,583, US 10,080,814 and US 10,143,764
    - New P&G product – Febreze TOUCH
- ACE–M2 and ACE–M2R (Weitz/Lu – Harvard)
  - Extended observation times by orders of magnitude
  - Characterization of features unique to long-term evolution





ACE PI Publications Include …

J. Sprakel, A. Zaccone, F. Spaepen, P. Schall and D.A. Weitz, Direct Observation of Entropic Stabilization of Bcc Crystals near Melting, *Phys. Rev. Lett.* **118**, 088003 (2017).

T.E. Kodger, P.J. Lu, G.R. Wiseman and D.A. Weitz, Stable, Fluorescent Polymethylmethacrylate Particles for the Long-Term Observation of Slow Colloidal Dynamics, *Langmuir* **33**, 6382 (2017).

T. Yang, B. Sprinkle, Y. Guo, J. Qian, D. Hua, A. Donev, D.W.M. Marr, and N. Wu, Reconfigurable Microbots Folded from Simple Colloidal Chains *Proceedings of the National Academy of Sciences of the USA*, 2020

Yang T, Tasci TO, Neeves KB, Wu N, Marr DWM. Magnetic microlassos for reversible cargo capture, transport, and release, *Langmuir*. 2017 Jun 13;33(23):5932-7.

Sam Wilken, Rodrigo E. Guerra, Dov Levine, and Paul M. Chaikin, “Random Close Packing as a Dynamical Phase Transition,” *Phys. Rev. Lett*. 127, 038002 – 16 July 2021.

Galloway, K. Lawrence, Ma, Xiaoguang, Keim, Nathan C., Jerolmack, Douglas J., Yodh, Arjun G., and Arratia, Paulo E., Scaling of relaxation and excess entropy in plastically deformed amorphous solids. *Proceedings of the National Academy of Sciences* 117, 11887-11893 (2020).

Ma, X., Davidson, Z.S., Still, T., Ivancic, R.J.S., Schoenholz, S.S., Liu, A.J., and Yodh, A.G., Heterogeneous activation, local structure, and softness in supercooled colloidal liquids. *Physical Review Letters* 122, 028001 (2019).

What’s Next for Soft Matter Research?

- Future missions will follow recommendations from the current Decadal Survey

NASA/CP-20205010493

Grand Challenges in Soft Matter Science: Prospects for Microgravity Research

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What's Next for Soft Matter Research?

Grand Challenges

Grand Challenges

- Machines Made out of Machines
- Scalable Self-sustaining Ecosystems
- Active Materials and Metamaterials

Grand Challenge: Machines Made Out of Machines

Machines Made Out of Machines

— All living things are machines made of machines

— Networks with interacting elements

— Linear and equilibrium was the 20th Century; the 21st is non-linear and non-equilibrium

— Self-repair, compute, and learn

"While 19th century science invented equilibrium thermodynamics and statistical mechanics, and the 20th learned to apply these methods to understand the equilibrium properties of soft matter, the focus of the 21st century is non-equilibrium statistical mechanics, phenomena and dynamics, ranging from the physics of swimming to understanding the origin of life."

Grand Challenges in Soft Matter Science: Prospects for Microgravity Research

The Path Forward

Assumptions

— Microgravity required: ". . .in terrestrial gravity the driving, temperature, concentration, magnetic, electric and light fields create density gradients and produce flows which interfere with the basic phenomena we wish to study. ***Microgravity allows us to isolate the fundamental interactions and dissect the phenomena***"

— Instrumentation required: ". . . soft-matter science often deals with microscopic, micron-scale, samples. A nanoliter droplet can contain ~106 active particles, easily enough for most experiments. A ***microscope can capture full high-resolution images*** of this (100µm)3 region. Many of the basic instruments needed for space research have been developed. ***What is needed is automation, large quantity sample handling and exchange, the ability to change sample properties continuously***

— Community required: A dynamic field requires more than a handful of investigators

Notional Solicitation Content

Solicitation Content

- Develop general principles leading to equations of motion for non-equilibrium self-assembly
  - Force potentials
  - Chemical activity and flow
  - Hydrodynamic interactions and motors
  - Self-assembly far from equilibrium
- Motility induced phase separation
  - Active systems driven by light, chemistry, surface tension, and electric fields
  - Flows trapping particles without an interaction potential
  - Spontaneous chirality
- Non-equilibrium, non-linear systems and the interface to self-organizing biological systems